Supporting Information

The Contribution of Anaerobic Digesters to Emissions Mitigation and Electricity Generation Under U.S. Climate Policy

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Economic Model Framework

The Emissions Prediction and Policy Analysis (EPPA) model is a recursive dynamic, computable general equilibrium (CGE) model of the global economy that links GHG emissions to economic activity. The model is maintained by Joint Program on the Science and Policy of Global Change at the Massachusetts Institute of Technology, and has been widely used to evaluate climate policies (see, for example, refs. [1, 2]). Ref. [3] describes the model in detail and the source code is available at http://globalchange.mit.edu/. Version 5 of the EPPA models the world economy and identifies the U.S., 15 other regions and 13 sectors, including livestock, energy-intensive industry, and electricity. Reflecting EPPA's focus on energy systems, electricity can be produced using conventional technologies (for example, electricity from coal and gas) and advanced technologies (for example, large scale wind generation and electricity from biomass). Advanced technologies enter endogenously when they become economically competitive with existing technologies. Refined oil includes refining from crude oil, shale oil, and liquids from biomass, which compete on an economics basis and can be used for transportation. EPPA is calibrated using economic data from the Global Trade Analysis Project (GTAP) database [4], energy data from the International Energy Agency [5], and non-CO_2 GHG and air pollutant from the Emission Database for Global Atmospheric Research (EDGAR) 3.2 database [6, 7]. The model is solved through time, in five-year increments, by imposing exogenous growth rates for population and labor productivity.

To represent ADs in the EPPA model, we include manure as a livestock byproduct and specify AD production functions. We stipulate that the livestock sector produces manure for 1000, 500 and 250kW digesters and pasture manure in fixed proportion to output, with base-year quantities equal to spatial grouping quantities outlined in the main text. In our core scenarios, we include separate production functions for 1000, 500 and 250kW ADs, but we do not allow anaerobic digestion of manure from pasture. Each AD production function combines manure and other inputs to produce output (Figure S1). Manure and transport services are used in fixed proportions, and the manure-transport composite is used in fixed proportions with a capital-labor aggregate. Substitution between capital and labor is allowed (σ_{KL} = 1), reflecting tradeoffs between capital and labor costs. ADs also use other industry in fixed proportion to output. ADs produce electricity and CO_2e allowances (methane credits) in fixed proportions. AD production functions are parameterized using cost data from Table S2, averaged over the four distance bands for each digester. Electricity used on farm will be valued at the retail price while electricity sold to utility companies will be sold at the wholesale price. As we do not track digester electricity use, we assume that all electricity from digesters is sold at the retail price, reflecting the possibility that electricity not used on farm may be sold directly to consumers (at the retail price). In an unreported sensitivity analyzes, to consider the sale of electricity from ADs to utilities at a reduced price, we valued electricity from digesters at three-quarters of the retail price. Results from these analyzes were similar to those reported in the paper."

When ADs using pasture manure are permitted, we assume that AD operating costs equal those for 500kW digesters, but impose higher other industry expenses to reflect manure collection costs. The average markup for pasture AD electricity over conventional electricity is 2.03. As methane producing bacteria does not form in pasture manure, ADs using pasture manure do not produce methane credits.

Under the economy-wide cap imposed in our analysis, agricultural producers must submit allowances for emissions from all sources, including emissions from direct energy use, manure management and enteric fermentation. In our framework, as is common in climate policy studies, the allocation of allowances will not influence production decisions. This is because there is an opportunity cost associated with the use of a "free" allowance, which is equal to the cost of purchasing an allowance.

The reference scenario in our analysis does not include policies that will influence GHG emissions, such as the Energy Independence and Security Act and the California Renewable Portfolio Standard (RPS). While the inclusion of such policy in the baseline is required to assess the additional costs of a particular climate policy, a reference without any climate-related policies allows us to assess the total impact of climate policies on the adoption of ADs

Modeling Anaerobic Digesters

We model a modified plug-flow anaerobic digester (AD) that uses livestock manure as an input, and generates electricity. Biogas is made up of methane, carbon dioxide and traces of other compounds, such as hydrogen sulfide. The typical digester produces biogas with 60-70% methane and 30-40% carbon dioxide [8]. Our study includes representative

1000kW, 500kW and 250kW ADs, and we will describe the 1000kW AD here, as the same methodology was used for all three AD sizes.

Assuming a capacity factor of 80%, a 1000kW AD would produce 7,000,000 kWh/year. A typical generator of this size can perform at a 40% efficiency [8]. Therefore, the equivalent energy input of 17,500,000 kWh is needed as an input to the 1000kW digester for one year. While the amount and source of livestock manure would vary between ADs in practice, in our simulations we assume the manure is from a representative sample of livestock in the U.S., based on methane emissions from manure management as described by EPA (2010). Swine and dairy cattle each account for 44% of methane manure emissions, and poultry and beef cattle each account for 6%. Manure management methane emissions from sheep, goats and horses are disregarded in this analysis. To calculate the number of each type of animal whose manure is input into the AD, we use a modified version of an equation from ref. [9] to estimate the methane production of AD systems. For each animal type (dairy cattle, beef cattle, swine and poultry), the number of livestock units producing manure for ADs, L, is determined by:

$$L = MP /(TAM/1000 \times VS \times B_0 \times 0.662 \times 365.25)$$

where MP is methane production (kg/yr), VS is volatile solids production rate (kg VS/1000 kg animal mass-day), TAM is typical animal mass (kg/head), B_0 is maximum CH_4 producing capacity (CH_4 m^3/kg VS), 0.662 is the density of methane at 25°C (kg CH_4/m^3 CH4) and 365.25 is the number of days/year. Data on TAM, VS and B_0 are weighted averages of ref. [9] data for state level livestock populations, and manure data for each livestock type at the state level is taken from [10]. Therefore, a typical 1000kW digester in our analysis uses manure combined from approximately 11,000 swine, 3,000 dairy cattle, 500 beef cattle and 40,000 poultry. Manure excretion rates were used to estimate the total mass of manure input based on ref. [11], with a typical AD consuming almost 90,000 tonnes of manure annually.

To calculate the methane mitigation potential from business as usual manure management practices, we followed, ref. [9] (Section 3.10), supplemented by state-level data from ref. [10]. We estimated that each 1000kW AD mitigated 7,000 tonnes of CO_2e/yr.

While this study modeled a "representative" anaerobic digester that would be used across the United States, we acknowledge that each installation will vary depending on availability, quantity and quality of manure or other inputs, opportunities for sales or use of digestate, use or sale of biogas, and several other variables. Given the relatively few ADs in the US, it was challenging to robustly parameterize our model, and therefore included several generalizations and assumptions (which are documented in the manuscript). As future ADs are planned and installed, it is essential that data be collected on the operations, economics and environmental outcomes for use in future scientific and policy related endeavors.

Alternative scenarios

Our core scenarios assumed that manure from pasture-fed livestock was not available for ADs, and AD electricity production was the only option to decrease emissions from manure management. In two alternative scenarios, we independently tested an optimistic assumption about the development of pasture manure collection technologies, and allowed farmers to flare biogas to receive emissions credits.

Under our optimistic pasture manure collection assumptions, generation costs from pasture manure were similar to 500kW generation costs. As manure deposited on pasture does release methane given the aerobic conditions, pasture manure entering ADs did not receive emissions credits. Pasture manure increases potential AD generation capacity by 7000MW. ADs from pasture manure entered in 2050, and AD electricity generation increased to 0.4 PWh, 9 percent of total electricity generation, and welfare increased and the CO_2e price decreased relative to our core policy scenario with digesters (Table S4).

When we allow biogas flaring, methane can be flared at no additional cost and methane destroyed by flaring earns carbon credits. Methane can also be used to produce electricity (and earn carbon credits) at the same costs as in our core scenarios. The choice between flaring and using methane to produce electricity is determined endogenously in the model on an economic basis. For low electricity prices, flaring is the best option, while producing electricity from methane becomes economically viable as the electricity price rises.

The results for this scenario are reported in Table S5. Under lower carbon prices in early years, all methane from manure management is flared. However, in later years, as higher carbon prices raise the price of electricity, electricity production from ADs becomes profitable. Cumulative emissions mitigation from manure management increase by 175 Mt CO_2e when methane flaring is an option relative to when methane credits can only be gained from AD electricity production. Overall, these results suggest that biogas flaring presents a viable near-term emissions mitigation option for farmers, and increases the scope for manure management to decrease emissions.

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Table S1: State electricity generation potential

State	1000kW (MW potential)	500kW (MW potential)	250kW (MW potential)	Total MW Potential	Rank	% of electricity generation
Iowa	1,029	2		1,031	1	13.6
California	870	92	32	994	2	3.3
Texas	593	163	58	814	3	1.4
Nebraska	636	-	1	637	4	13.8
Minnesota	591	27	10	628	5	8.0
North Carolina	592	2	5	599	6	3.4
Wisconsin	528	13	7	548	7	6.0
Ohio	418	70	4	492	8	2.2
Kansas	458	23	-	481	9	7.2
Indiana	456	9	2	467	10	2.5
Pennsylvania	451	1	8	460	11	1.4
Illinois	279	24	4	307	12	1.1
Colorado	200	65	39	303	13	4.0
Michigan	254	27	13	293	14	1.8
Missouri	230	47	13	290	15	2.2
Georgia	208	26	14	248	16	1.3
Idaho	185	38	22	245	17	14.3
Arkansas	219	16	9	244	18	3.1
New York	194	13	8	215	19	1.1
Florida	167	23	6	196	20	0.6
South Dakota	106	51	24	181	21	17.9
Oklahoma	118	24	21	163	22	1.5
Washington	107	32	17	155	23	1.0
Alabama	101	26	8	135	24	0.6
New Mexico	45	25	42	112	25	2.1
Virginia	53	22	15	89	26	0.9
Kentucky	48	27	7	82	27	0.6
South Carolina	75	1	6	81	28	0.6
Arizona	28	25	25	78	29	0.5
Oregon	20	22	35	77	30	0.9
Maine	63	9	4	76	31	3.1
Mississippi	32	32	12	75	32	1.1
Utah	42	14	15	71	33	1.1
Maryland	57	5	2	64	34	0.9
New Jersey	11	42	1	54	35	0.6
Tennessee	14	15	14	43	36	0.3
Connecticut	34	7	2	43	37	1.0
Vermont	22	11	1	34	38	3.4
North Dakota	2	24	6	32	39	0.7
Montana	2	27	1	29	40	0.7
Louisiana	6	11	6	23	41	0.2
West Virginia	16	2	2	20	42	0.2
Rhode Island	3	16	-	19	43	1.8
Delaware	14	2	-	16	44	1.4
Massachusetts	7	7	2	16	45	0.3
Wyoming	5	4	3	11	46	0.2
New Hampshire	1	4	4	9	47	0.3
Nevada	1	-	0	1	48	0.0
Total (MW)	9,591	1,155	524	11,270		

Table S2: Calculation of levelized cost of electricity

#	Description	Units	Source	1000kW AD - 225,400,626,900 Sq km	500kW AD - 225,400,626,900 Sq km	250kW AD - 225,400,626,900 Sq km
1	Overnight Capital Cost	$/kW	refs. 14 & 15	3,134	4,170	5,548
2	Total Capital Requirement	$/kW	[1]+([1]*.04*2yrs)	3,385	4,504	5,992
3	Capital Recovery Charge Rate	%	ref. 16	10.6%	10.6%	10.6%
4	Fixed O&M	$/kW	ref. 17	101.54	135.11	179.76
5	Project Life	years	Assumption	20	20	20
6	Capacity Factor	%	Assumption	80%	80%	80%
7	Operating Hours	Hours	[6]*8760 (hours/yr)	7,008	7,008	7,008
8	Capital Recovery Required	$/kWh	[2]*[3]/[7]	0.05	0.07	0.09
9	Fixed O&M Recovery Required	$/kWh	[4]/[7]	0.01	0.02	0.03
10	Levelized Cost of Electricity	$/kWh	[4]+[8]+[9]	0.066	0.087	0.116
11	Transportation Cost per kWh	$/kWh	Own calculations; refs. 12 & 18	0.06, 0.08, 0.08, 0.10	0.06, 0.08, 0.08, 0.010	0.06, 0.08, 0.08, 0.010
12	Transmissions and Distribution	$/kWh	ref. 16	0.020	0.020	0.020
13	Cost of Electricity	$/kWh	[10]+[11]+[12]	0.15, 0.16, 0.17, 0.18	0.17, 0.18, 0.19, 0.20	0.20, 0.21, 0.22, 0.23
14	Markup Over Conventional elec.		[13]/0.095	1.52, 1.69, 1.78, 1.91	1.76, 1.92, 2.01, 2.13	2.06, 2.23, 2,31, 2.44

Table S3: Additional economic and emissions model outputs for reference and policy scenarios

	Scenario	Unit	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Livestock Production	Reference	index	11.6	12.3	14.3	16.1	18.0	20.3	23.3	26.6	30.4	35.0
Livestock Production	No Digesters	index	11.6	12.3	14.0	15.6	17.3	19.4	22.1	25.1	28.3	31.3
Livestock Production	Digesters	index	11.6	12.3	14.0	15.6	17.4	19.6	22.5	25.7	29.3	33.5
Economy GHG Emissions	Reference	Mt CO2e	7,036	6,861	7,551	7,847	8,160	8,567	9,016	9,461	9,911	10,403
Economy GHG Emissions	No Digesters	Mt CO2e	7,036	6,706	6,044	5,719	5,398	5,081	4,766	4,451	4,132	3,808
Economy GHG Emissions	Digesters	Mt CO2e	7,036	6,706	6,044	5,719	5,450	5,140	4,842	4,542	4,237	3,930
Electricity Price	Reference	cents/kWh	8.3	9.1	9.9	10.4	11.0	11.6	12.1	12.5	12.8	13.1
Electricity Price	No Digesters	cents/kWh	8.3	9.1	12.4	14.0	16.1	18.4	19.6	21.2	23.2	27.2
Electricity Price	Digesters	cents/kWh		0	35	55	76	102	139	159	184	274
AD Electricity Sales	Digesters	billion $	-	-	-	-	1.3	1.6	2.3	2.9	3.5	4.5
AD CO2e Sales	Digesters	billion $	-	-	-	-	0.3	0.5	0.8	1.1	1.5	2.5
Manure $/kWh (1000kW)	Digesters	dollars $	-	-	-	-	0.01	0.03	0.06	0.08	0.10	0.18
Manure $/kWh (500kW)	Digesters	dollars $	-	-	-	-	-	-	0.03	0.05	0.07	0.15
Manure $/kWh (250kW)	Digesters	dollars $	-	-	-	-	-	-	-	0.01	0.03	0.11
AD Electricity (all)	Digesters	PWh	-	-	-	-	0.10	0.12	0.15	0.18	0.21	0.24
AD Electricity (1000kW)	Digesters	PWh	-	-	-	-	0.10	0.12	0.14	0.15	0.18	0.20
AD Electricity (500kW)	Digesters	PWh	-	-	-	-	-	-	0.02	0.02	0.02	0.02
AD Electricity (250kW)	Digesters	PWh	-	-	-	-	-	-	-	0.01	0.01	0.01
% of AD Elec. of all Elec.	Digesters	%	-	-	-	-	2.6	2.9	3.6	4.2	4.7	5.4

Table S4: Economic and emissions indicators from scenario when manure from pasture was diverted to ADs.

	Unit	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Economic Welfare	billion $	8,434	8,452	9,980	11,203	12,603	14,365	16,358	18,506	20,894	23,557
CO2e Price	$/tonne	-	-	35	55	76	102	139	159	184	268
Economy GHG Emissions	Mt CO2e	7,036	6,706	6,044	5,719	5,450	5,140	4,842	4,542	4,237	3,931
Livestock GHG Emissions	Mt CO2e	158	163	146	161	125	140	150	166	189	177
Electricity Price	cents/kWh	8.3	9.1	12.4	14.0	15.8	17.8	19.5	20.9	22.4	25.5
Electricity Production	PWh	3.9	4.1	4.0	4.1	4.1	4.1	4.2	4.3	4.4	4.4
AD Electricity Production	PWh	-	-	-	-	0.1	0.1	0.2	0.2	0.2	0.4
AD Electricity Production (Pasture)	PWh	-	-	-	-	-	-	-	-	-	0.1
Livestock Production	index	11.6	12.3	14.0	15.6	17.4	19.6	22.5	25.7	29.3	33.5
AD Electricity Sales	billion $	-	-	-	-	1.3	1.6	2.3	2.9	3.5	4.5
AD CO2e Sales	billion $	-	-	-	-	0.3	0.5	0.8	1.1	1.5	2.4

Table S5: Economic and emissions indicators from scenario when flaring is available in addition to electricity generation by ADs.

	Unit	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Economic Welfare	billion $	8,434	8,452	9,982	11,206	12,607	14,371	16,372	18,529	20,918	23,567
CO2e Price	$/tonne	-	-	33	54	77	109	137	159	184	275
Economy GHG Emissions	Mt CO2e	7,036	6,749	6,095	5,775	5,460	5,151	4,846	4,542	4,238	3,930
Livestock GHG Emissions	Mt CO2e	158	168	147	163	179	200	227	180	205	156
AD GHG Mitigation	Mt CO2e	-	-	-	-	-	-	-	78	89	113
Flaring GHG Mitigation	Mt CO2e	-	44	50	56	62	70	80	14	15	6
Electricity Price	cents/kWh	8.3	9.1	12.2	14.0	15.9	18.2	19.6	20.9	22.4	25.7
Electricity Production	PWh	3.9	4.1	4.0	4.1	4.1	4.1	4.2	4.3	4.4	4.4
AD Electricity Production	PWh	-	-	-	-	-	-	-	0.2	0.2	0.2
Livestock Production	index	11.6	12.3	14.1	15.8	17.6	19.7	22.6	25.8	29.4	33.5
AD Electricity Sales	billion $	-	-	-	-	-	-	-	2.5	3.0	4.4
AD CO2e Sales	billion $	-	-	-	-	-	-	-	1.0	1.3	2.4

Table S6: Economic and emissions indicators from scenario with an increase of 30 percent mitigation from ADs.

	Unit	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Economic Welfare	billion $	8,434	8,452	9,980	11,203	12,604	14,368	16,360	18,512	20,901	23,569
CO2e Price	$/tonne	-	-	35	55	76	99	138	159	183	272
Economy GHG Emissions	Mt CO2e	7,036	6,706	6,044	5,719	5,466	5,168	4,871	4,570	4,270	3,970
Livestock GHG Emissions	Mt CO2e	158	163	146	161	110	113	123	140	159	142
Electricity Price	cents/kWh	8.3	9.1	12.4	14.0	15.8	17.7	19.4	20.9	22.3	25.6
Electricity Production	PWh	3.9	4.1	4.0	4.1	4.1	4.1	4.2	4.3	4.4	4.4
AD Electricity Production	PWh	-	-	-	-	0.11	0.13	0.16	0.18	0.21	0.24
AD Electricity (1000kW)	PWh	-	-	-	-	0.11	0.12	0.14	0.16	0.18	0.20
AD Electricity (500kW)	PWh	-	-	-	-	-	0.01	0.02	0.02	0.02	0.02
AD Electricity (250kW)	PWh	-	-	-	-	-	-	0.01	0.01	0.01	0.01
Livestock Production	index	11.6	12.3	14.0	15.6	17.4	19.7	22.6	25.9	29.6	33.9
AD Electricity Sales	billion $	-	-	-	-	1.3	1.8	2.4	2.9	3.5	4.6
AD CO2e Sales	billion $	-	-	-	-	0.4	0.7	1.1	1.5	1.9	3.2

Figure S1: Production structure for ADs in the EPPA model.

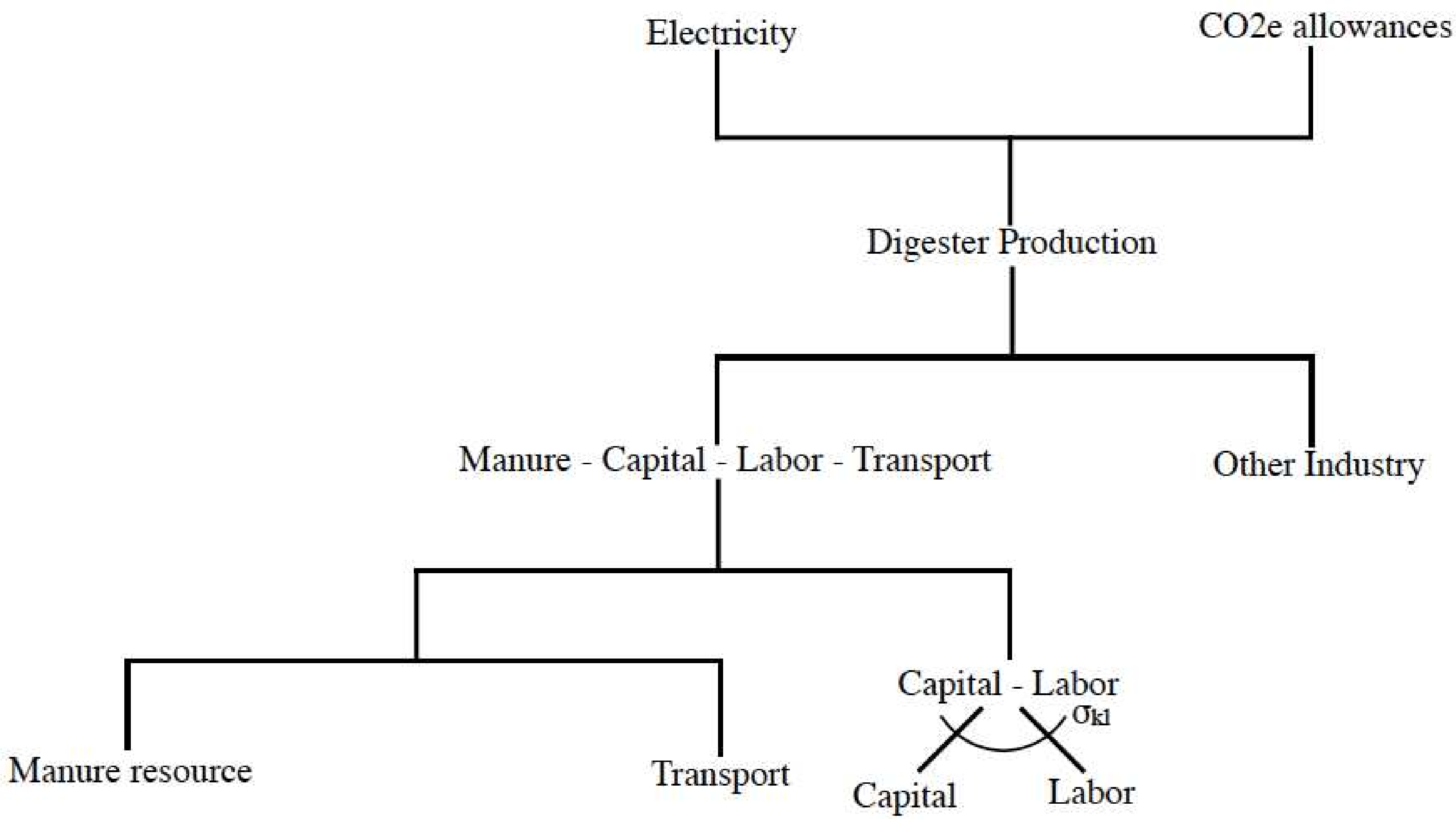

Figure S2: U.S. Electricity generation in reference (a) and policy-no digesters (b) scenarios. Note: Advanced fossil includes natural gas combined cycle (NGCC), NGCC with sequestration, integrated gasification with combined cycle and sequestration, and wind with gas backup.